

FeynHiggs2.2: A Precision Tool for the MSSM Higgs Sector

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based on collaboration with
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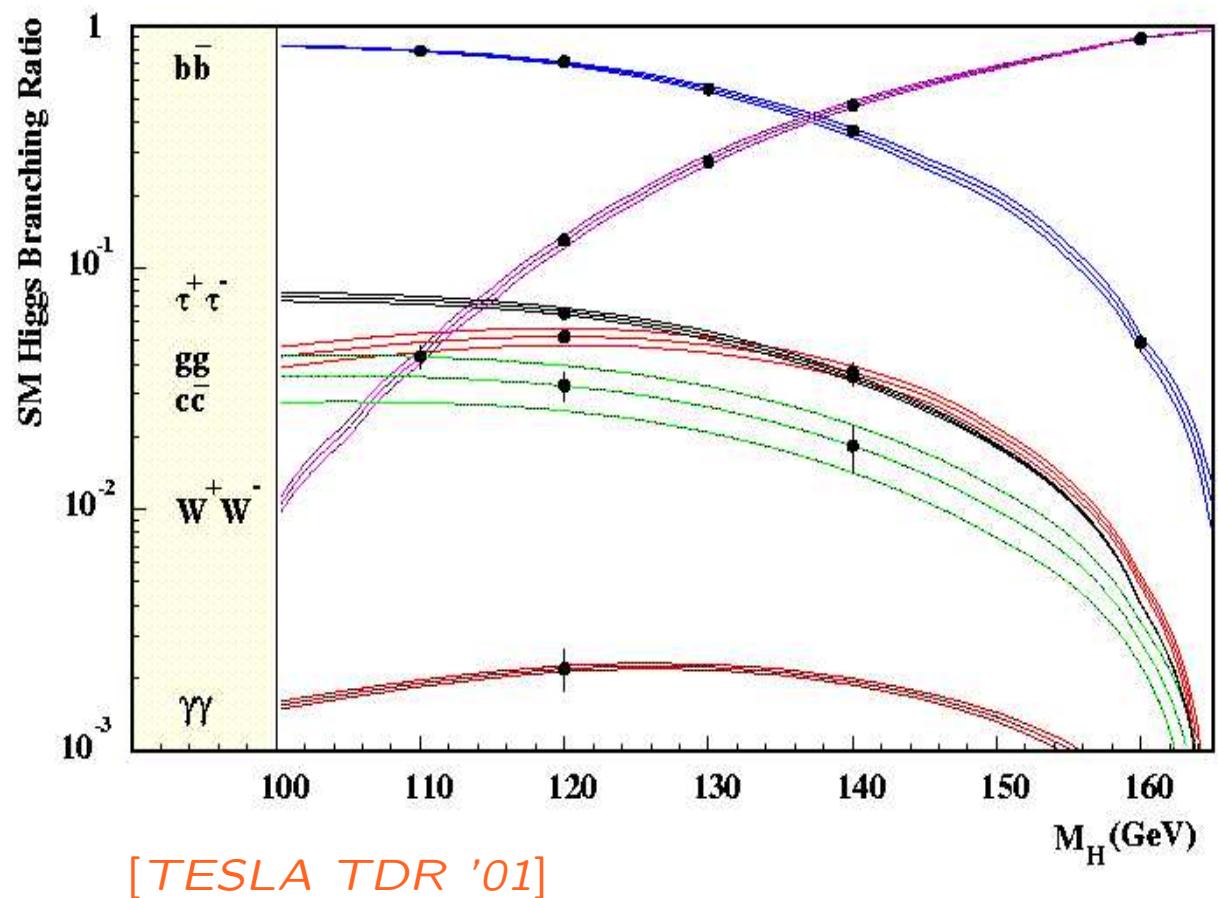
- 1.** Motivation
- 2.** The code FeynHiggs2.2
- 3.** How to install FeynHiggs2.2
- 4.** How to run FeynHiggs2.2
- 5.** Conclusions

1. Motivation

SM Higgs @ LC:

Precise measurement of:

1. Higgs boson mass,
 $\delta M_H \approx 50 \text{ MeV}$
2. Higgs boson width
(direct/indirect)
3. Higgs boson couplings,
 $\mathcal{O}(\text{few}\%) \Rightarrow$
4. Higgs boson quantum
numbers: spin, ...



MSSM: similar precision expected (possible problems from loop corrections)

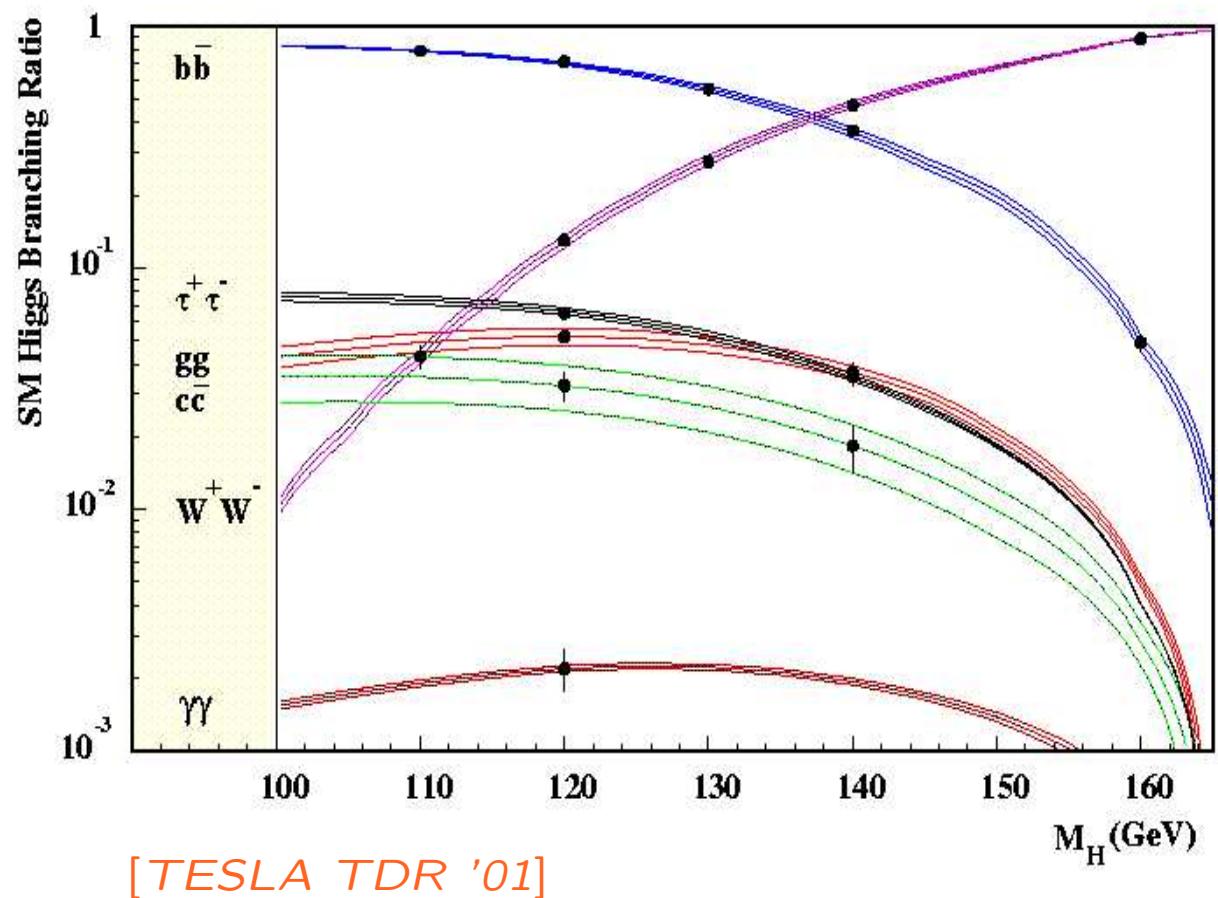
Q: Can this precision be utilized in the MSSM Higgs sector?

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MSSM: similar precision expected (possible problems from loop corrections)

Q: Can this precision be utilized in the MSSM Higgs sector?

A: Yes! . . . if the theory predictions are as precise

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{\text{gauge couplings, in contrast to SM}} |H_1 \bar{H}_2|^2$$

physical states: h^0, H^0, A^0, H^\pm

Goldstone bosons: G^0, G^\pm

Input parameters:

$$\tan \beta = \frac{v_2}{v_1}, \quad M_A^2 = -m_{12}^2 (\tan \beta + \cot \beta)$$

Contrary to the SM:

m_h is not a free parameter

MSSM tree-level bound: $m_h < M_Z$, excluded by LEP Higgs searches

Large radiative corrections:

Dominant one-loop corrections:

$$\Delta m_h^2 \sim G_\mu m_t^4 \ln \left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \right)$$

The MSSM Higgs sector is connected to all other sector via loop corrections (especially to the scalar top sector)

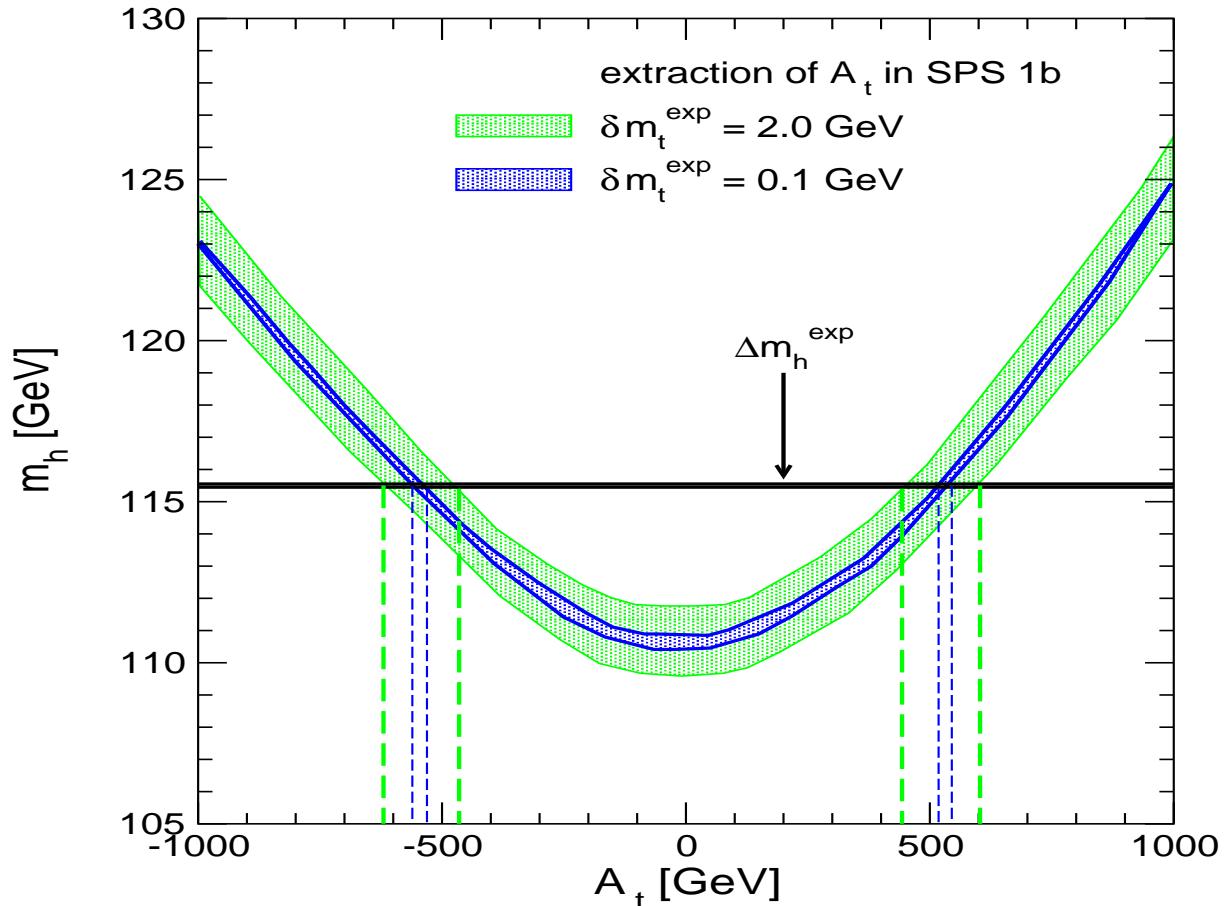
Measurement of m_h , Higgs couplings \Rightarrow test of the theory

LHC: $\Delta m_h \approx 0.2$ GeV, LC: $\Delta m_h \approx 0.05$ GeV

\Rightarrow aim for theoretical precision!

($\Rightarrow m_h$ will be (the best?) electroweak precision observable)

Example of application: m_h prediction as a function of A_t



SPS1b:

$m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{b}_1}, m_{\tilde{b}_2}$ known,
 A_t unknown

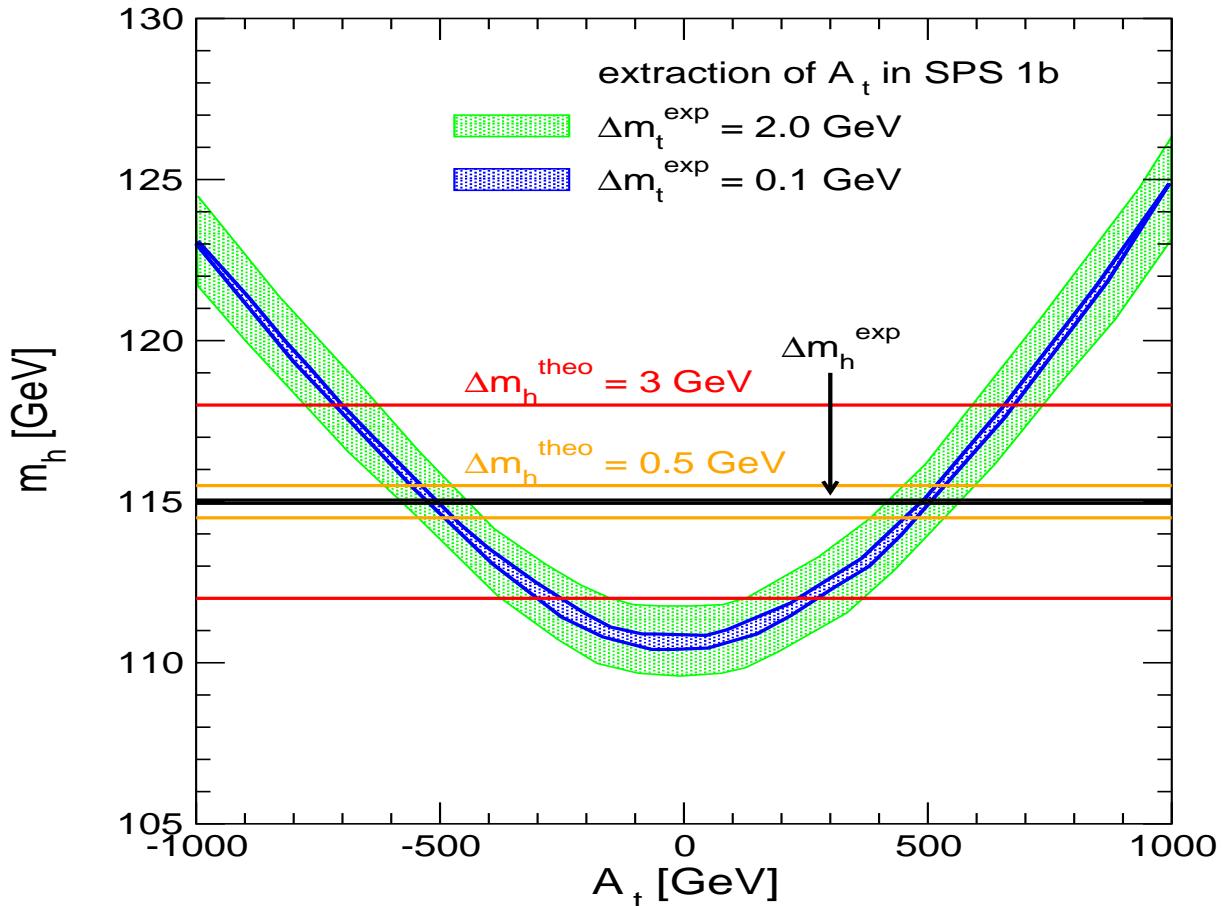
$\tan \beta, M_A$ known,
realistic parametric
errors assumed

(from SUSY exp. errors)

⇒ extraction of A_t possible
Theory error neglected

⇒ m_h is crucial input for SUSY fit programs (Fittino, Sfitter)

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The complex case:

Higgs potential of the cMSSM contains two Higgs doublets:

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = e^{i\xi} \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - \cancel{m_{12}^2} (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{\text{gauge couplings, in contrast to SM}} |H_1 \bar{H}_2|^2$$

Five physical states: h^0, H^0, A^0, H^\pm (no \mathcal{CPV} at tree-level)

2 \mathcal{CP} -violating phases: $\xi, \arg(m_{12}) \Rightarrow$ can compensate each other

Input parameters: $\tan \beta = \frac{v_2}{v_1}, M_A$ or M_{H^\pm}

Effects of complex parameters in the Higgs sector:

Complex parameters enter via loop corrections:

- μ : Higgsino mass parameter
- $A_{t,b,\tau}$: trilinear couplings $\Rightarrow X_{t,b,\tau} = A_{t,b} - \mu^* \{\cot \beta, \tan \beta\}$ complex
- $M_{1,2}$: gaugino mass parameter (one phase can be eliminated)
- $m_{\tilde{g}}$: gluino mass

\Rightarrow can induce \mathcal{CP} -violating effects

Result:

$$(A, H, h) \rightarrow (\textcolor{red}{h}_3, \textcolor{red}{h}_2, \textcolor{red}{h}_1)$$

with

$$m_{h_3} > m_{h_2} > m_{h_1}$$

Inclusion of higher-order corrections:

(→ Feynman-diagrammatic approach)

Propagator / mass matrix with higher-order corrections:

$$\begin{pmatrix} q^2 - M_A^2 + \hat{\Sigma}_{AA}(q^2) & \hat{\Sigma}_{AH}(q^2) & \hat{\Sigma}_{Ah}(q^2) \\ \hat{\Sigma}_{HA}(q^2) & q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\ \hat{\Sigma}_{hA}(q^2) & \hat{\Sigma}_{hH}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

$\hat{\Sigma}_{ij}(q^2)$ ($i, j = h, H, A$) : renormalized Higgs self-energies

$\hat{\Sigma}_{Ah}, \hat{\Sigma}_{AH} \neq 0 \Rightarrow \mathcal{CP}\text{V}$, \mathcal{CP} -even and \mathcal{CP} -odd fields can mix

Our result for $\hat{\Sigma}_{ij}$:

- full 1-loop evaluation: dependence on all possible phases included
- New: $\mathcal{O}(\alpha_t \alpha_s)$ corrections in the FD approach
rMSSM: difference between FD and RGEP approach \mathcal{O} (few GeV)

Result: $(A, H, h) \rightarrow (h_3, h_2, h_1)$ with $m_{h_3} > m_{h_2} > m_{h_1}$

Higgs boson couplings:

(in $q^2 = 0$ approximation)

$$\begin{pmatrix} h_3 \\ h_2 \\ h_1 \end{pmatrix} = \begin{pmatrix} u_{11} & u_{12} & u_{13} \\ u_{21} & u_{22} & u_{23} \\ u_{31} & u_{32} & u_{33} \end{pmatrix} \cdot \begin{pmatrix} A \\ H \\ h \end{pmatrix}$$

- h_1, h_2, h_3 : neutral Higgs boson with \mathcal{CPV} couplings
- $u_{12}, u_{13}, u_{21}, u_{31}$: \mathcal{CPV} mixings
- u_{ij} determine Higgs-fermion and Higgs-gauge boson couplings

2. The code FeynHiggs2.2

Latest version: FeynHiggs2.2.8 (04/05)

real MSSM:

(→ mostly relevant for CDM calculations)

contains all available higher-order corrections
to Higgs boson masses and couplings

FeynHiggs contains

- full 1 loop calculations
- all available 2 loop calculations (leading and subleading)
- very leading 3 loop contributions

complex MSSM:

contains nearly all available results
(we are working on the rest)

www.feynhiggs.de

Included in FeynHiggs2.2 (I):

Evaluation of all Higgs boson masses and mixing angles (rMSSM/cMSSM)

- $m_{h_1}, m_{h_2}, m_{h_3}, M_{H^\pm}, \alpha_{\text{eff}}, u_{ij}, \dots$

Evaluation of all neutral Higgs boson decay channels (rMSSM/cMSSM)

- total decay width Γ_{tot}
- $\text{BR}(h_i \rightarrow f\bar{f})$: decay to SM fermions
- $\text{BR}(h_i \rightarrow \gamma\gamma, ZZ^{(*)}, WW^{(*)}, gg)$: decay to SM gauge bosons
- $\text{BR}(h_i \rightarrow h_1 Z^{(*)}, h_1 h_1)$: decay to gauge and Higgs bosons
- $\text{BR}(h_i \rightarrow \tilde{f}_i \tilde{f}_j)$: decay to sfermions
- $\text{BR}(h_i \rightarrow \tilde{\chi}_i^\pm \tilde{\chi}_j^\pm, \tilde{\chi}_i^0 \tilde{\chi}_j^0)$: decay to charginos, neutralinos

Evaluation for the SM Higgs (same masses as the three MSSM Higgses)

- total decay width $\Gamma_{\text{tot}}^{\text{SM}}$
- $\text{BR}(h_i^{\text{SM}} \rightarrow f\bar{f})$: decay to SM fermions
- $\text{BR}(h_i^{\text{SM}} \rightarrow \gamma\gamma, ZZ^{(*)}, WW^{(*)}, gg)$: decay to SM gauge bosons

Included in FeynHiggs2.2 (II):

Evaluation of all charged Higgs boson decay channels (rMSSM/cMSSM)

- total decay width Γ_{tot}
- $\text{BR}(H^+ \rightarrow f\bar{f}')$: decay to SM fermions
- $\text{BR}(H^+ \rightarrow h_i W^+)$: decay to gauge and Higgs bosons
- $\text{BR}(H^+ \rightarrow \tilde{f}_i \tilde{f}'_j)$: decay to sfermions
- $\text{BR}(H^+ \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^+)$: decay to charginos and neutralinos

Evaluation of additional couplings:

- $g(V \rightarrow V h_i, h_i h_j)$: coupling of gauge and Higgs bosons
- $g(h_i h_j h_k)$: all Higgs self couplings (including charged Higgs)
- $\sigma(\gamma\gamma \rightarrow h_i)$: Higgs production XS at a γC

Included in FeynHiggs2.2 (III):

Evaluation of theory error on masses and mixing

→ estimate of uncertainty in m_h from unknown higher-order corrections

Evaluation of masses, mixing and decay in the NMfv MSSM

NMfv: Non Minimal Flavor Violation

⇒ Connection to Flavor physics

[S.H., W. Hollik, F. Merz, S.P. '04]

Evaluation of additional constraints (rMSSM/cMSSM)

- ρ -parameter: $\Delta\rho$ at $\mathcal{O}(\alpha)$, $\mathcal{O}(\alpha\alpha_s)$, ...
 $\Delta\rho \gtrsim 2 \times 10^{-3}$ indicates experimentally disfavored \tilde{t}/\tilde{b} masses
- anomalous magnetic moment of the μ : $(g_\mu - 2)_{\text{SUSY}}$

Planned:

- $\text{BR}(b \rightarrow s\gamma)$ and similar observables
- EDMs of electron, neutron, Hg, ...

3. How to install FeynHiggs2.2

1. Go to www.feynhiggs.de
2. Download the latest version
3. type `./configure, make, make install`
⇒ library `libFH.a` is created
4. 3 possible ways to use *FeynHiggs*:
 - A) as a `stand alone program`
 - B) `called from a Fortran/C++ code`
 - C) `called within Mathematica`
processing of `Les Houches Accord` data possible
5. Detailed `instructions` and `help` are provided in the `man pages`

Alternative: On-line version

1. Go to www.feynhiggs.de/fhucc
2. Enter your parameters on-line in the web page
3. Obtain your results with a mouse click

⇒ for single points and checks of your downloaded version of FeynHiggs
⇒ always the latest version

⇒ online presentation

Also man pages are available on-line

4. How to run FeynHiggs2.2

A) Stand alone program

- Prepare **input file**:

MSusy	500
MA0	1000
TB	5
Abs(At)	800
Qt	0

...

loops possible for one or two parameters (\rightarrow scan)

- call *FeynHiggs*:

./FeynHiggs var.in 40030231

var.in : input file (any name possible)

40020211 : options (precision, real/complex MSSM, ...)

Qt 0 : input parameters $\overline{\text{DR}}$ or on-shell

- output to screen (human readable)

output to file (machine readable) (\rightarrow see man pages)

Possible screen output:

```
...
| TB          =      5.000000
| MA0         =    200.000000           input parameter
| MHp         =   -1.000000
| MSusy       =    500.000000
...
| MStop        =  441.2194  601.6737           derived parameters
...
| mssmpart    = 4
| tanbren     = 0           options
...
| Mh1          =    117.186672           Higgs masses
...
| UHiggs       =    0.99589960    0.09046538    0.00000000
|                  -0.09046538    0.99589960    0.00000000
|                  0.00000000    0.00000000    1.00000000
...
| DeltaMh0     =    0.919435           Uncertainties
...

```

B) Called from a Fortran/C++ code

Link *FeynHiggs* as a subroutine \Rightarrow link libFH.a

call FHSetFlags(...) :

→ specification of accuracy etc.

call FHSetPara(...) :

→ specify input parameters

call FHGetPara(...) :

→ obtain derived parameters

call FHHiggsCorr(...) :

→ obtain Higgs boson masses and mixings

call FHUncertainties(...) :

→ obtain theory error on Higgs boson masses and mixings from unknown higher-order corrections

call FHCouplings(...) :

→ obtain decay widths, BRs etc.

C) Called within Mathematica

- install the math link to *MFeynHiggs* , e.g.:

`Install[''MFeynHiggs'']`

- `FHSetFlags[...]` :

→ specification of accuracy etc.

`FHSetPara[...]` :

→ specify input parameters

`FHGetPara[]` :

→ obtain derived parameters

`FHHiggsCorr[]` :

→ obtain Higgs boson masses and mixings

`FHUncertainties[]` :

→ obtain theory error on Higgs boson masses and mixings from unknown higher-order corrections

`FHCouplings[]` :

→ obtain decay widths, BRs etc.

Processing SUSY Les Houches Accord data

(SLHA: [P. Skands et al. '03])

(I/O routine: [T. Hahn '04])

- call *FeynHiggs* with input file (from spectrum generator, . . .)

`./FeynHiggs Isajet.spc 40020211`

FeynHiggs checks whether input file is in SLHA format

`Isajet.spc` : input file

`40020211` : options (as before)

- *FeynHiggs* reads all necessary data
- *FeynHiggs* evaluates the Higgs boson masses, couplings, BRs, etc.
- `Isajet.spc.fh` is created

all input data remains

Higgs masses and mixing angles are overwritten

Higgs BRs etc. are added

5. Conclusions

- Very precise MSSM Higgs sector evaluation necessary for
 - reliable bounds on e.g. $m_{1/2}$
 - reliable calculations e.g. in the funnel region
- *FeynHiggs2.2* provides Higgs boson masses, mixing angles, couplings, branching ratios, etc.
in the MSSM with/without complex parameters (and for NMHV)
- *FeynHiggs2.2* is available at www.feynhiggs.de
- On-line version is available at www.feynhiggs.de/fhucc
- Possible:
Stand alone vers. - call within Fortran/C++ - call within Mathematica
- Processing of Les Houches Accord data

Back-up slides

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

$$[u, d, c, s, t, b]_{L,R} \quad [e, \mu, \tau]_{L,R} \quad [\nu_{e,\mu,\tau}]_L \quad \text{Spin } \frac{1}{2}$$

$$[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}]_{L,R} \quad [\tilde{e}, \tilde{\mu}, \tilde{\tau}]_{L,R} \quad [\tilde{\nu}_{e,\mu,\tau}]_L \quad \text{Spin } 0$$

$$g \quad \underbrace{W^\pm, H^\pm}_{\gamma, Z, H_1^0, H_2^0} \quad \text{Spin 1 / Spin 0}$$

$$\tilde{g} \quad \tilde{\chi}_{1,2}^\pm \quad \tilde{\chi}_{1,2,3,4}^0 \quad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales

\tilde{t}/\tilde{b} sector of the MSSM: (scalar partner of the top/bottom quark)

Stop, sbottom mass matrices ($X_t = A_t - \mu^*/\tan\beta$, $X_b = A_b - \mu^*\tan\beta$):

$$\mathcal{M}_{\tilde{t}}^2 = \begin{pmatrix} M_{\tilde{t}_L}^2 + m_t^2 + DT_{t_1} & m_t X_t^* \\ m_t X_t & M_{\tilde{t}_R}^2 + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m_{\tilde{t}_1}^2 & 0 \\ 0 & m_{\tilde{t}_2}^2 \end{pmatrix}$$

$$\mathcal{M}_{\tilde{b}}^2 = \begin{pmatrix} M_{\tilde{b}_L}^2 + m_b^2 + DT_{b_1} & m_b X_b^* \\ m_b X_b & M_{\tilde{b}_R}^2 + m_b^2 + DT_{b_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{b}}} \begin{pmatrix} m_{\tilde{b}_1}^2 & 0 \\ 0 & m_{\tilde{b}_2}^2 \end{pmatrix}$$

mixing important in stop sector (also in sbottom sector for large $\tan\beta$)

soft SUSY-breaking parameters A_t, A_b also appear in ϕ - \tilde{t}/\tilde{b} couplings

$$SU(2) \text{ relation} \Rightarrow M_{\tilde{t}_L} = M_{\tilde{b}_L}$$

\Rightarrow relation between $m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}, \theta_{\tilde{b}}$